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A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss

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[1] Satellite-derived estimates of sea-ice age and thickness are combined to produce a proxy ice thickness record for 1982 to the present. These data show that in addition to the well-documented loss of perennial ice cover as a whole, the amount of oldest and thickest ice within the remaining multiyear ice pack has declined significantly. The oldest ice types have essentially disappeared, and 58% of the multiyear ice now consists of relatively young 2- and 3-year-old ice compared to 35% in the mid-1980s. Ice coverage in summer 2007 reached a record minimum, with ice extent declining by 42% compared to conditions in the 1980s. The much-reduced extent of the oldest and thickest ice, in combination with other factors such as ice transport that assist the ice-albedo feedback by exposing more open water, help explain this large and abrupt ice loss. **Citation:** Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery (2007), A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss, *Geophys. Res. Lett.*, *34*, L24501, doi:10.1029/2007GL032043.

1. Introduction

[2] Over the past two decades, reductions in the amount of Arctic sea ice that survives summer melt have resulted in more newly formed ice (first-year ice) and less of the relatively thick, old ice that makes up the perennial ice cover [e.g., *Johannessen et al.*, 1999; *Comiso*, 2002; *Belchansky et al.*, 2004; *Nghiem et al.*, 2006; *Kwok*, 2007]. While these studies effectively describe the extent of multiyear ice (MYI; defined here as ice that has survived at least one melt season), little is known about changes within the MYI cover itself. Such changes are significant since MYI that has survived several melt seasons is assumed to be thicker than younger MYI, so any change in the age distribution of ice within the perennial pack should also result in a net loss of ice volume.

2. Changes in Sea-Ice Age

[3] Using satellite data and drifting buoys, it is possible to observe the formation, movement, and disappearance of sea ice. This history can then be used to estimate ice age, as shown by *Fowler et al.* [2004] and *Rigor and Wallace* [2004]. In the *Fowler et al.* [2004] approach, ice movement is calculated using a cross-correlation technique applied to sequential, daily satellite images acquired by the Scanning Multichannel Microwave Radiometer (SMMR), the Special Sensor Microwave/Imager (SSM/I), and the series of Advanced Very High Resolution Radiometer (AVHRR) sensors. Motion vectors are then blended via optimal interpolation with International Arctic Buoy Program drifting-buoy vectors [*Fowler*, 2003]. Using the resulting gridded vector fields for 1979 through summer 2007, ice age can then be estimated by treating each grid cell that contains ice as an independent Lagrangian particle and advecting the particles at weekly time steps. Ice that survives summer melt is considered to have aged for one year, or an additional year in the case of MYI. *Fowler et al.* [2004] and *Rigor and Wallace* [2004] provide further details.

[4] Maps of ice age for March in individual years (Figure 1) show the continued transformation to a younger ice pack described by *Johannessen et al.* [1999], but also illustrate shifts in age distribution within the remaining perennial pack. The area where at least half of the ice fraction in March consists of ice that is at least 5 years old has decreased by 56%, from 5.83×10^6 km^2 in 1985 to a minimum of 2.56×10^6 km^2 in 2007. Most of the perennial pack now consists of ice that is 2 or 3 years old (58% in March 2006 vs. a minimum of 35% in March 1987). The fraction of 5+ year old ice within the MYI decreased from 31% in 1988 to 10% in 2007. Older ice types have essentially disappeared, decreasing from 21% of the ice cover in 1988 to 5% in 2007 for ice 7+ years old. The greatest change in age distribution occurred within the central Arctic Basin. In this area (region 1, Figure 1), 57% of the ice pack was 5 or more years old in 1987, with 25% of this ice at least 9 years old. By 2007 however, the coverage of ice 5+ years old decreased to 7%, and no very old ice (9 + years old) has survived. From 2004 onward, and in particular in 2006 and 2007, the remaining oldest ice has been confined to a small portion of the Arctic (regions 6–8); essentially a relict of the perennial ice cover of 20 years ago.

3. Relationship Between Ice Age and Thickness Within the Perennial Sea Ice Cover

[5] The significance of this transition to a younger MYI pack in terms of overall change in ice volume depends on the assumption that older MYI is thicker than younger MYI. If this assumption is valid, it should be possible to use age as a proxy for thickness, just as thickness has been used to infer age in sonar data [e.g., *Tucker et al.*, 2001; *Yu et al.*, 2004]. For MYI as a whole, the fact that first-year ice (FYI) is thinner than MYI is well documented. Thus, areal coverage of MYI, retrieved from microwave data [e.g., *Belchansky et al.*, 2004; *Nghiem et al.*, 2006; *Kwok*,

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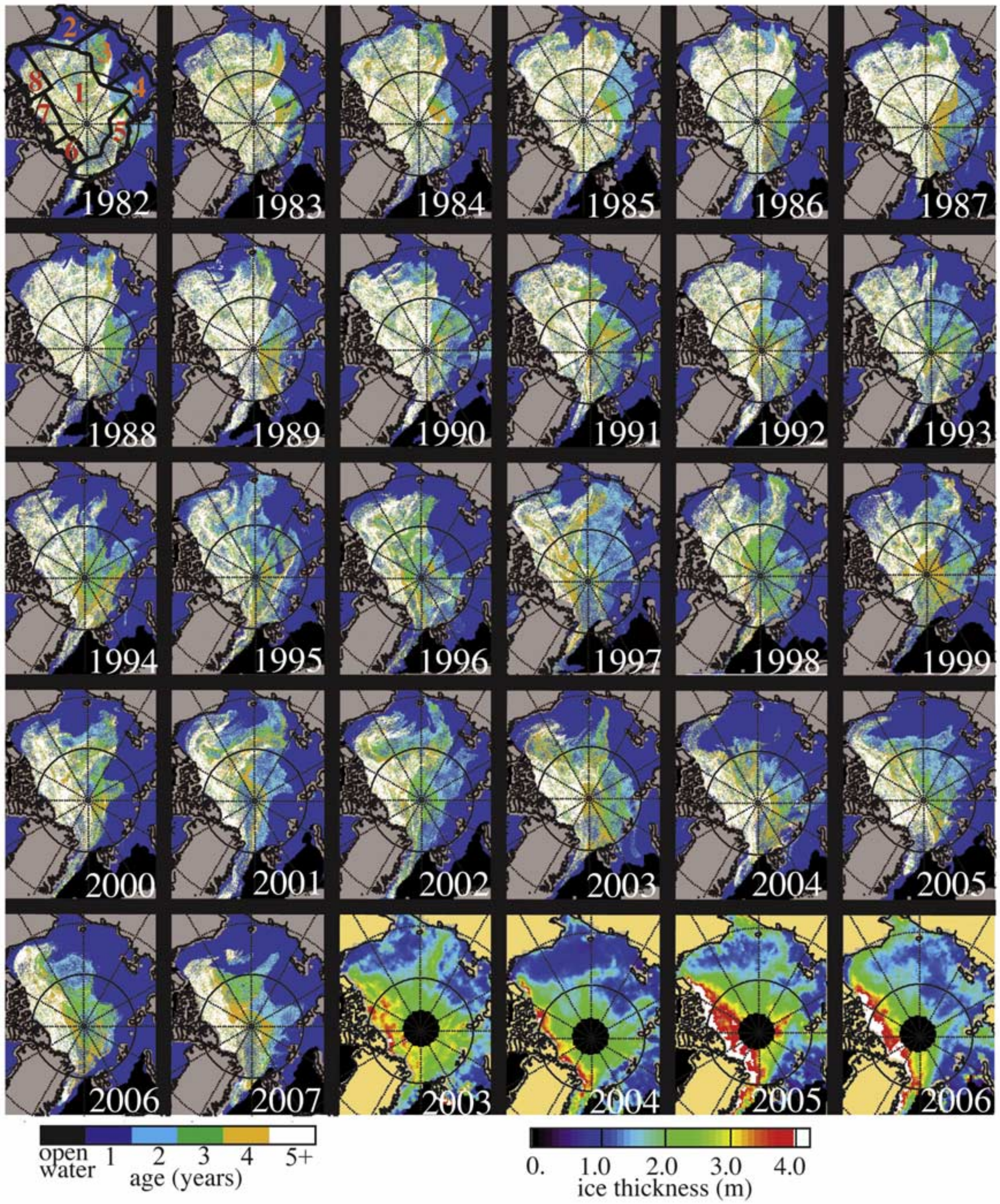

Figure 1. Sea ice age for each year from March 1982 through March 2007 (panels with gray land mask). Eight regions used for analysis are indicated in the first panel. ICESat-derived ice thickness for spring 2003, spring 2004, spring 2005, and spring 2006 are shown in the last four panels with yellow land masks. An animation of the weekly age data is available at http://ccar.colorado.edu/∼jimm/age_movie1.mov.

2007] or from the extent of ice at the end of summer [*Comiso*, 2002], provides an overall idea of thickness changes. However, these data contain no direct information on changes within the MYI pack itself.

[6] Ice thicknesses estimated from Ice, Cloud, and land Elevation Satellite (ICESat) Geoscience Laser Altimeter System (GLAS) [*Kwok et al.*, 2004; *Zwally et al.*, 2007] data provide a spatially extensive data set that, when combined with the age data described above, can serve as the basis for a proxy ice thickness record. Toward this end, ICESat-derived ice thicknesses estimated from ice freeboard and composited over each February to March period for 2003–2006 at 50 km cell size [*Saba et al.*, 2004; *Zwally et al.*, 2007] were regridded to match the Equal Area Scalable Earth (EASE)-grid age data. The resulting thickness maps correspond well with the spatial patterns of ice age (last 4 panels in Figure 1). To quantify this apparent relationship, the co-registered thickness and age data for spring 2003–2006 were used to calculate mean thickness as a function of age. The effects of different ages within each 50km ICESat

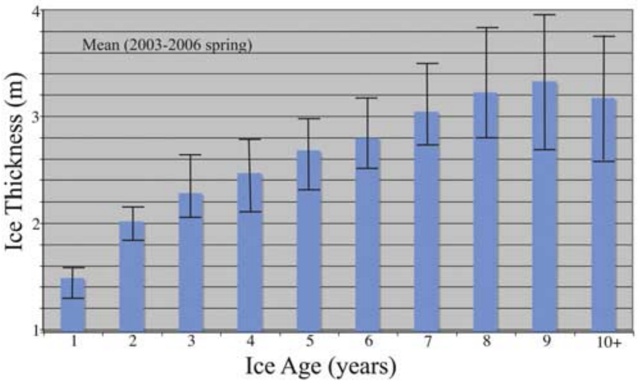

Figure 2. Mean 2003–2006 spring ice thicknesses as a function of age. The ranges of mean thicknesses over the 4 years are indicated.

grid cell were minimized by calculating the fraction of each age category using the 16 12.5 km ice-age grid cells within each ICESat cell, and then estimating mean ice thickness for each age category using only those ICESat grid cells that contained at least 80% ice of a particular age. Mean thicknesses were calculated in this manner for each of the 4 years and then averaged into 4-year means. Figure 2 shows that the 4-year mean thicknesses increase nearly linearly with age, at a rate of 0.19 myr^{-1} (correlation coefficient R of 0.96). Individual-year values were 0.13 myr^{-1} (R = 0.93), 0.15 myr^{-1} (R = 0.90), 0.24 myr^{-1} (R = 0.97) and 0.17 myr^{-1} (R = 0.75) for 2003–2006, respectively. The increase with age is less after the ice reaches about 3 m thickness, the approximate limit for thermodynamical ice growth. In addition to growth through freezing, thickness is added due to kinematic effects such as ridging and rafting, which are also a function of age since they accumulate over time [*Tucker et al.*, 2001].

[7] Using the 4-year mean thicknesses for each age category, a data set of proxy ice thicknesses for the month of March, 1982–2007 was then produced from the gridded age data by replacing the ice age value at each grid cell for a given year with the mean thickness corresponding to ice of that age, i.e.,

$$H_{I_{proxy}}(x,y) = \overline{H}_{I_{age_{(n)}}}(x,y)$$

Where H_{Iproxy} (x, y) is the proxy ice thickness in meters at grid cell x, y, and $\overline{H}_{I_{age_{(n)}}}(x,y)$ is the ICESat-based 4-year mean ice thickness for ice of age n at grid cell x, y, where n = 1 to 10 and $\overline{H}_{I_{age_{(n)}}}(x,y)$ = (1.49 m, 2.02 m, 2.28 m, 2.47 m, 2.68 m, 2.80 m, 3.05 m, 3.23 m, 3.33 m, 3.18 m) for first-year ice through 10-year-old ice.

[8] To further validate the age vs. thickness relationship for years prior to ICESat, we compared the age-derived thicknesses to 12 sets of sonar ice-draft data [*National Snow and Ice Data Center*, 1998; *Wensnahan and Rothrock*, 2005], collected in spring over 8 years (1986, 1987, 1988, 1990, 1991, 1993, 1994, 1999). The sonar data were sampled along relatively few individual tracks in each year, so the age/thickness vs. draft comparisons are limited by coverage and by spatial mismatches. Nevertheless, the increase in draft with age is apparent for some tracks, with correlations typically increasing when comparisons are limited to younger ice types (e.g. 1 to 5 years old). The latter is due in part to positional errors, which accumulate over time in the age data.

[9] It is important to note that since the ICESat data span only 4 years, the proxy time series of ice thickness changes do not take into account overall thinning of the ice over time apparent in ice draft from sonar data [*Tucker et al.*, 2001; *Yu et al.*, 2004]. Such overall thinning due to melt and reduced ice growth would need to be added to arrive at total changes in thickness. Also, the ICESat-derived thickness product used here is generated using several assumptions that affect accuracy [*Zwally et al.*, 2007]. These include use of climatological snow depths and spatially- and temporally-invariant densities for snow, ice and water. Future enhancements will improve the thickness estimates, but the correlation seen here between age and ICESat-derived thickness suggests that the existing product, and the proxy thickness record estimated for 1982–2007, are sufficiently accurate to assess spatial and temporal variability.

[10] Analysis of these proxy thickness data for March of each year suggests that the bulk of the ice loss associated with depletion of the older ice types has occurred in the eastern Arctic (Figure 3), as inferred by *Nghiem et al.* [2006] using MYI extent estimated from QuikSCAT data. The pattern of greatest ice loss in the western and Siberian Arctic agrees with ice model simulations [e.g., *Rothrock et al.*, 2003]. Ice thickness has increased slightly in a few locations adjacent to the Canadian Archipelago and in the eastern Beaufort Sea (regions 6–8 in Figure 1), also consistent with modeling studies [e.g., *Holloway and Sou*, 2002], but this increase does not compensate for loss elsewhere. Thickness averaged over the Arctic Basin recovered slightly in the late 1990s [*Rothrock et al.*, 2003]. Since then however, the thinning associated with the transition to a younger ice cover has continued in the central Arctic and in the mean averaged over all regions. *Rothrock et al.* [2003] found the greatest thickness changes in the central and eastern Arctic rather than in the Beaufort and Chukchi seas, which agrees with the thickness change in Figure 3e. However, since that time, the thinning has shifted toward the Pacific sector of the Arctic (Figure 3f). Overall, these results are consistent with thickness changes observed in sonar data [e.g., *Tucker et al.*, 2001; *Yu et al.*, 2004], which were attributed mainly to loss of the oldest, thickest ice types.

4. Conditions in Summer 2007

[11] Ice cover in summer 2007, as estimated from passive microwave data (i.e., the Sea Ice Index used by *Stroeve et al.* [2007]), continues the general downward trend seen over the satellite period, reaching record lows in ice extent and area (Figure 4). In September, extent was 4.28×10^6 km^2; 39% below the long-term mean (1979–2000) and 23% below the previous September minimum in 2005. The decrease in extent between 2006 and 2007 is 41% larger than the previous largest year-to-year decrease. Ice area (which in the microwave-derived products includes some effects from surface melt as well as actual open water) is

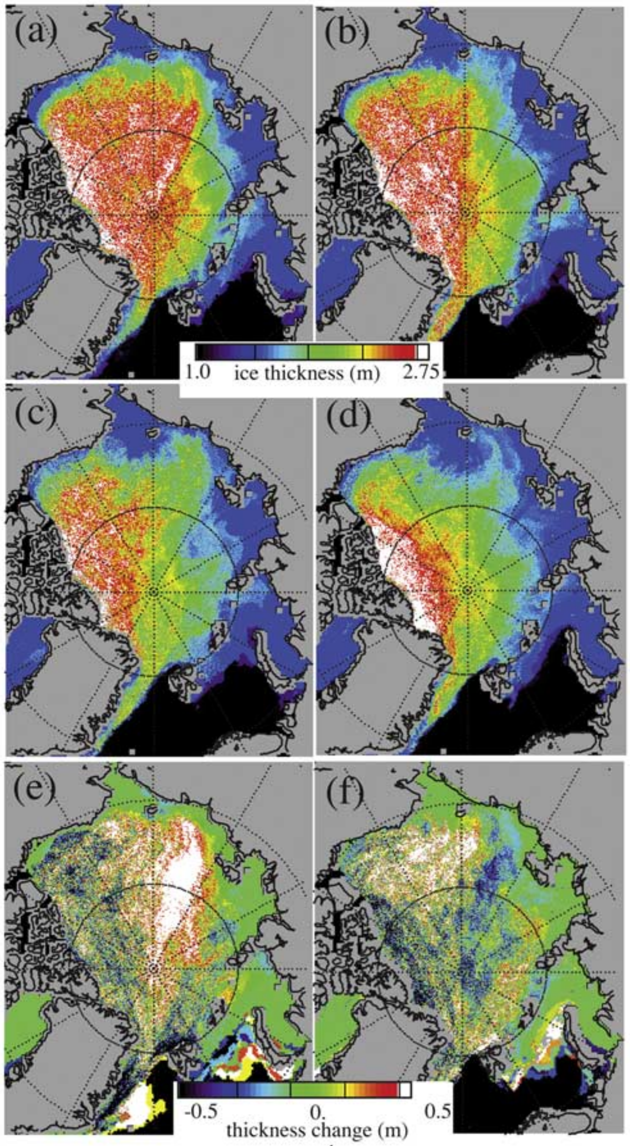

Figure 3. Mean spring ice thickness for (a) 1982–1987, (b) 1988–1995, (c) 1996–2000, and (d) 2001–2007. (e) Mean 1982–1987 thickness minus mean 1993–1996 thickness. (f) Mean 1993–1996 thickness minus mean 2001–2007 thickness.

41% below the long-term mean, 44% below the mean for 1986–1997, and 31% less than in 2005.

[12] The losses in extent and area this summer correspond to the regions in the western Arctic where ice age has decreased the most, with the consolidated ice pack retreating to the edge of ice that is at least 3 years old (or about 2.2 m thick in the proxy thickness data). Leading up to these summer conditions, sea level pressure (SLP) in spring was below normal over Siberia and the Laptev Sea, similar to the positive Northern Annular Mode (NAM) conditions that reduced MYI extent in the Siberian Arctic in the late 1980's–early 1990's [e.g., *Rigor and Wallace*, 2004]. In summer, a high pressure cell over the western Beaufort Sea and northern Canada coupled with below-normal SLP over Siberia and Europe yielded persistent southerly winds over the western Beaufort, Chukchi and East Siberian seas, favoring northward ice drift and warmer temperatures. This dipole pressure pattern has become more frequent in recent years, contributing to ice losses in the western Arctic since the late 1990s [*Maslanik et al.*, 2007]. However, the dipole occurs primarily in winter and spring; persistence of this pattern through summer is unusual. Associated with the extensive high-pressure area over the western Arctic, cloud cover was below normal, allowing more solar heating of the ice and water surface, which in turn accelerates the ice-albedo feedback.

5. Discussion

[13] This extreme and abrupt loss of ice cover in 2007, following the extensive and sustained reduction in the oldest, thickest ice beginning in the late 1980s, is consistent with the premise that younger, thinner ice is likely to be more sensitive to melt and to area loss due to ridging and rafting, with a variety of implications for the basic nature of the Arctic Ocean [e.g., *McPhee et al.*, 1998]. The change in ice thickness from the late 1980s to mid 1990s (Figure 3e) shows the effects of the highly positive phase of the NAM, with strong counterclockwise transport in the eastern Arctic moving older ice northward to be replaced by first-year ice, and exporting old ice south through Fram Strait. The changes in age and thickness from the mid-1990s to the mid part of the current decade reflect a different circulation pattern, where cross-Arctic transport from the Pacific side of the Arctic to the Atlantic side is prevalent [e.g., *Maslanik et al.*, 2007]. The result is loss of ice in the Chukchi and

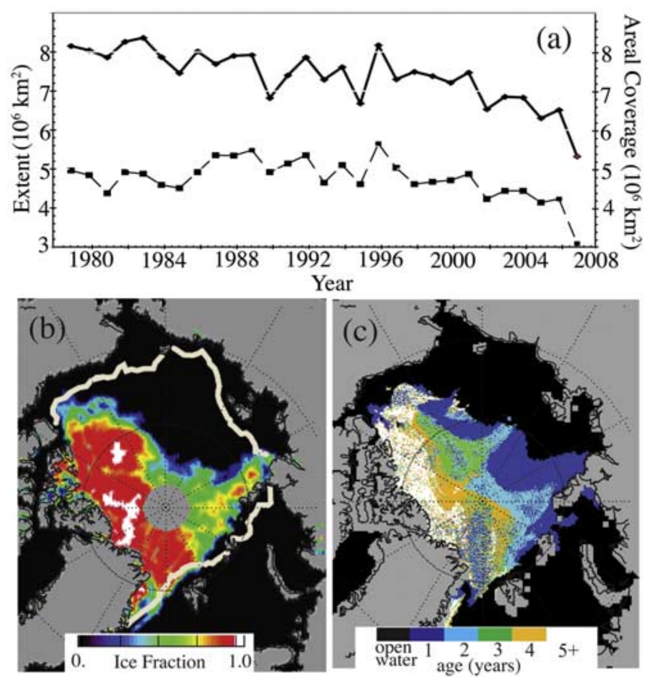

Figure 4. (a) Time series of ice extent (solid line) and fractional coverage (dashed line), estimated using the NSIDC Sea Ice Index passive-microwave data set. (b) SSM/I ice fraction on 15 Sept. 2007 and (c) ice age for mid-August 2007. Median (1979–2007) September ice extent is indicated by the white line in Figure 4b.

Beaufort seas earlier in the period, combined with losses in the East Siberian Sea during the last 4 years, as seen in Figure 1. Over the past 10 years, thickness associated with ice age has increased in the Laptev Sea and the Fram and Nansen basins (e.g., Figure 3f), which were regions of ice loss from the late 1980s–mid 1990s. A return to strongly-positive NAM conditions or similar patterns would presumably remove much of this ice, further reducing the extent of the thickest portion of the perennial pack.

[14] Another significant change is the role of the Beaufort Gyre - the dominant wind and ice drift regime in the central Arctic. In the past, ice within the Gyre circulated for years within the Arctic Basin in a clockwise pattern while it aged and thickened [e.g., *Tucker et al.*, 2001]. Since the late 1990s however, as is apparent in Figure 1, ice typically has not survived the transit through the southern portion of the Beaufort Gyre, severing the previously continuous, clockwise journey of the MYI. The western Arctic Basin is therefore acting as a new area of "ice export" where MYI is removed through a combination of transport and melt. Hence, rather than helping to replenish the old, thick ice, a strengthened Gyre under current conditions instead assists in the transition to a younger, less extensive perennial ice cover.

[15] Other ice properties also vary with age. For example, ice strength generally increases with age due to brine drainage [e.g., *Kovacs*, 1996], so a shift toward younger ice means that on average, the ice cover can more easily compress upon itself via ridging and rafting, producing more open-water area that in turn reduces surface albedo and absorbs more heat, comparable to conditions in 1997–1998 that likely contributed to substantial ice loss in the Beaufort Sea [*McPhee et al.*, 1998]. This process adds a dynamical component that strengthens the ice-albedo feedback.

6. Conclusions

[16] Analysis of satellite-derived sea-ice age data and a new proxy record of ice thickness for 1982–2007 shows that in addition to less multiyear ice overall in the Arctic, the mean age and thickness of ice within the remaining multiyear ice pack have decreased due to loss of the oldest ice types, and the remaining older and thicker ice is now confined to a much smaller portion of the Arctic Ocean than in earlier years. Given this, the ice cover is likely to be increasingly susceptible to large, rapid reductions in ice extent and fractional coverage. Such extreme variability is particularly evident during the current summer when more ice was lost than during any previous summer on record, with ice extent and ice area reaching new lows that are well below the previous minima. The replacement of older, thicker ice by younger, thinner ice over much of the Arctic Ocean, combined with cumulative effects of warming, unusual atmospheric circulation patterns, and resulting intensification of the ice-albedo feedback, contributed to this large and abrupt loss of ice. Taken together, these changes suggest that the Arctic Ocean is approaching a point where a return to pre-1990s ice conditions becomes increasingly difficult and where large, abrupt changes in summer ice cover as in 2007 may become the norm.

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